

Studying Star and Planet Formation with the Submillimeter Probe of the Evolution of Cosmic Structure. S. A. Rinehart¹ and the SPECS Mission Study team. ¹NASA Goddard Space Flight Center, Code 665, Stephen.A.Rinehart@nasa.gov

Introduction: The Submillimeter Probe of the Evolution of Cosmic Structure (SPECS) is a far-infrared/submillimeter (40-640 μm s) spaceborne interferometry concept, studied through the NASA Vision Missions program. SPECS is envisioned as a 1-km baseline Michelson interferometer with two 4-meter collecting mirrors. To maximize science return, SPECS will have three operational modes: a photometric imaging mode, an intermediate spectral resolution mode ($R \approx 1000\text{-}3000$), and a high spectral resolution mode ($R \approx 3 \times 10^5$). The first two of these modes will provide information on all sources within a 1 arcminute field-of-view (FOV), while the third will include sources in a small (≈ 5 arcsec) FOV. With this design, SPECS will have angular resolution comparable to the Hubble Space Telescope (50 mas) and sensitivity more than two orders of magnitude better than Spitzer (5σ in 10ks of $\approx 3 \times 10^7$ Jy Hz). We present here some of the results of the recently-completed Vision Mission Study for SPECS, and discuss the application of this mission to future studies of star and planet formation.

Science with SPECS: The capabilities of a mission as ambitious as SPECS are staggering. As part of the Vision Mission Study, we explored a variety of science applications for SPECS, ranging from the evolution of galaxies to the formation and evolution of debris disks. SPECS will make major contributions to several areas of interest to this meeting.

Gas and Debris Disks: After young stars lose their gas disks, they host debris disks consisting of dust, planetismals, and young planets. Young debris disks are likely in the terrestrial planet formation phase, while older disks correspond to the clearing or "heavy bombardment" phase. Through gravitational interaction with protoplanets, the debris disk can be distorted, forming gaps, clumps, and warps. These structures can be quite small, and in order to image such structures with high fidelity, very high angular resolution is required. SPECS, like ALMA, will be able to detect structures of 0.5 AU around sources at 10 pc, and since the thermal emission from these disks peaks at about 100 μm , SPECS will be more sensitive to debris dust than either JWST or ALMA.

SPECS will also make contributions to studies of protoplanetary disks by directly observing the "snow line", the point outside of which ices are able to form. The existence of these ices may be a critical component for the core accretion models of giant

planet formation and delivery of volatiles to young terrestrial planets. Since water is of particular importance for the evolution of life (as we know it), the astronomical processes leading to the formation, destruction, and dissemination of water molecules are of great interest. Spatially resolved spectroscopy of molecules, including water ice and vapor, promises to elucidate the pathways by which terrestrial exoplanets might be supplied with water and the mechanism(s) by which giant planets form.

Star Formation: Star formation continues to be a poorly understood astronomical phenomenon, in large part due to the lack of information on protostellar collapse. Dust surrounding protostars make observations at short wavelengths difficult if not impossible, while in the infrared and submillimeter, the lack of angular resolution makes detection of the infall/collapse signature difficult, as this signature is obscured by other dynamical effects (e.g. cloud core rotation, turbulent motions, etc.). A high-angular resolution FIR mission will allow direct detection of infall signatures.

In addition, there are a large number of molecular lines observable in the FIR/Submm spectra of protostars. Detection of these lines will improve our understanding of the chemical and dynamical evolution that produces stars, disks, and planets. Previous SWAS and ISO observations have shown high water vapor abundances in star formation regions, thought to arise from areas which have been shock-heated to $\approx 400\text{K}$ [1]. As mentioned above, SPECS will be able to detect molecular emission, in an important wavelength range inaccessible to ALMA or JWST.

The high spatial and spectral resolution provided by SPECS will allow observations which will distinguish between competing dynamical effects in envelopes, outflows, and disks of protostars, improving our understanding of the nature and evolution of infalling material.

Population III stars: Another major scientific question which SPECS will address is the formation of the first stars. Results from the Wilkinson Microwave Anisotropy Probe (WMAP) suggest that massive stars were formed by the time the universe was about 200 Myr old ($z \approx 17 \pm 5$) [2,3], and fully formed galaxies and quasars have been detected at 800 Myr ($z > 6$) by the Sloan survey [4]. ISO and Spitzer have detected forbidden line emission in nearby active galactic nuclei. Forbidden emission

arises from ultraviolet-illuminated dusty regions (such as planetary nebulae). Similar emission, redshifted twenty-fold into the FIR/submm, arises in debris rings around Population III supernovae. Supermassive ($140\text{--}260 M_{\text{Solar}}$) Population III stars are believed to form in binaries, and when one of the pair undergoes pair-instability supernovae, it leaves behind a silicate dust shell. While similar emission from nearby regions has been studied, because of the high redshift and small angular size (20-100 mas) of the Population III ejecta rings, only with a high angular resolution FIR/submm mission can studies of these earliest stars be conducted. SPECS will illuminate our understanding of when and how these first stars formed in an extremely metal-poor environment, and how they have contributed to the metal enrichment of the universe.

Mission Concept: The SPECS mission study was begun with the consideration of a number of different science cases of relevance to this type of mission. We focused on a few of these science cases, including those mentioned above, in order to develop a list of requirements for SPECS. These requirements are:

1. Field-of-view of 1 arcmin.
2. Wavelength coverage of 40-640 μm .
3. Spectral resolution of 50 mas or better.
4. Ability to provide images in broad spectral bands, in photometry, in intermediate spectral resolution ($R=1000\text{--}3000$), and in high resolution for a small FOV ($R=3\times 10^5$).
5. Ability to obtain roughly one image per day, each image including spectral information for all sources within the FOV.
6. Ability to observe at least two nearby star formation regions.
7. Sufficient sensitivity to map extragalactic sources at high redshift.

These requirements could be satisfied by a number of different architectures. By following a decision-tree process, we examined technical issues derived from mission requirements, and developed a possible mission architecture for SPECS.

Mission Architecture: The mission architecture studied is a Michelson interferometer, consisting of two 4-meter light collectors connected to a central beam combiner by tethers. The interferometer operates in "double-Fourier" mode, where it makes use of the delay line to obtain both spectral and spatial information on a source. In short, the interferogram at every point in the synthetic aperture is the Fourier transform of the spectrum of the source at that spatial frequency. This "double-Fourier"

mode is particularly convenient because of the large delay line stroke required to obtain the requisite FOV [5]. By combining all of the interferograms from the different points in the synthetic aperture, one obtains a datacube which is a 3-D Fourier transform of the spectral/spatial information of the source. SPECS obtains information for all of the points of the synthetic aperture (the u-v plane) by rotating while reeling in/out the tethered collector telescopes. A prohibitive mass of thruster fuel would be required to achieve the u-v plane filling and satisfy requirement (5) with an untethered system.

Technical Challenges and Future Work: A number of technical issues remain for the development of SPECS. The use of tethers to control the motions of the collector telescopes, the development of the high-sensitivity detectors required, the fabrication of a massive long-stroke delay line, and the requirement of complex metrology systems are all outstanding challenges. We will study these different challenges in order to further develop the SPECS design.

The SPECS study was sponsored by NASA under the Vision Mission Concept study program.

Mission Study Team: Martin Harwit, PI (Cornell), Ron Allen (STSci), Dominic Benford (GSFC), Andrew Blain (Caltech), Claudio Bombardelli (CfA), Jason Budinoff (GSFC), Daniela Calzetti (STSci), Robert Chalmers (GSFC), Christine Cottingham (GSFC), William Danchi (GSFC), Michael DiPirro (GSFC), William Doggett (NASA-Langley), Pascale Ehrenfreund (Leiden), Nick Elias (Ball), Tracy Espero (Boeing), Neal Evans (UT Austin), Rodger Farley (GSFC), Robert Ferber (JPL), David Fischer (Ball), Jaqueline Fisher (NRL), Edward Friedman (Boeing), Tristram Hyde (GSFC), Andrew Jones (GSFC), Marc Kuchner (GSFC), Antoine Labeyrie (Obs. D'Haute Provence), Charles Lawrence (JPL), David Leisawitz (GSFC), Jim Leitch (Ball), Chuck Lilley (Northrop Grumman), Alice Liu (GSFC), Enrico Lorenzini (CfA), Richard Lyon (GSFC), Anthony Martino (GSFC), Cathy Marx (GSFC), John Mather (GSFC), Gary Melnick (CfA), Karl Menten (MPIfR), S. Harvey Moseley (GSFC), Lee Mundy (U. Md), Takao Nakagawa (ISAS/JAXA), Charley Noecker (Ball), David Neufeld (Johns Hopkins), Stan Ollendorf (GSFC), John Pearson (JPL), Dave Quinn (GSFC), Shobita Satyapal (George Mason), Eugene Serabyn (JPL), Mike Shao (JPL), Robert Silverberg (GSFC), Robert Smythe (JPL), Gordon Stacey (Cornell), H. Philip Stahl (NASA MSFC), Charles Townes (UC Berkeley), Wes Traub (CfA), Chirs Walker (U. Arizona), Alycia Weinberger (Carnegie Inst. Washington), Paul Whitehouse (GSFC), Mark Wilson (GSFC), Robert Woodruff (Lockheed Martin), Edward Wright (UCLA), and Harold Yorke (JPL).

References: [1] Harwit, et al. (1998) ApJ 497, L105. [2] Bennett, et al. (2003) ApJS 148, 1. [3] Spergel et al, (2003) ApJS 148, 175. [4] Fan et al. (2001) AJ 122, 2833. [5] Leisawitz, et al. (2002) Proc. SPIE 4852, 255.